

We claim:

- 1 1. A method of forming a virtual substrate comprised of an optoelectronic
2 device substrate and handle substrate comprising:
3 initiating bonding of the device substrate to the handle substrate, where
4 the device substrate is composed of a material suitable for fabrication of optoelectronic
5 devices therein and where the handle substrate is composed of an inexpensive material
6 suitable for providing mechanical support;
7 improving the mechanical strength of the device and handle substrates;
8 and
9 thinning the device substrate to leave a single-crystal film on the virtual
10 substrate such as by exfoliation of a device film from the device substrate.
- 1 2. The method of claim 1 further comprising providing a pre-bonding
2 treatment to allow the removal of a thin film.
- 1 3. The method of claim 1 further comprising cleaning and/or passivating the
2 device and/or handle substrates to facilitate bonding.
- 1 4. The method of claim 2 further comprising cleaning and/or passivating the
2 device and/or handle substrates to facilitate bonding.

1 5. The method of claim 2 where providing a pre-bonding treatment to allow
2 the removal of a thin film comprises ion implanting the device substrate to inject an
3 amount of gas species into the device substrate to form the internally passivated
4 surfaces and to create an internal pressure necessary to exfoliate a layer from the
5 device substrate upon annealing.

1 6. The method of claim 5 where ion implanting the device substrate
2 comprises implanting H^+ or a combination of H^+ and He^+ .

1 7. The method of claim 5 where ion implanting the device substrate
2 comprises implanting an etchant chosen according to the material of the device
3 substrate.

1 8. The method of claim 6 where ion implanting the device substrate
2 comprises implanting an etchant chosen according to the material of the device
3 substrate.

4 9. The method of claim 3 where cleaning and/or passivating the device and
5 handle substrates to facilitate bonding comprises passivating the surface of both the
6 device and handle substrates to allow hydrophobic wafer bonding.

1 10. The method of claim 9 where passivating the surface of both the device
2 and handle substrates comprises enabling the formation of an intimate covalent bond
3 between a device film, exfoliated from the device substrate, and the handle substrate in
4 the virtual substrate to allow for the ohmic, low-resistance interface electrical properties.

1 11. The method of claim 3 where cleaning and/or passivating the device and
2 handle substrates to facilitate bonding comprises eliminating adsorbed water on the
3 surface of the device and handle substrates by means of a low temperature bake in an
4 inert atmosphere or in vacuum.

1 12. The method of claim 11 where eliminating adsorbed water on the surface
2 of the device and handle substrates by means of a low temperature bake comprising
3 baking at a temperature such that the vapor pressure of water is below the partial
4 pressure of water in the surrounding ambient.

1 13. The method of claim 9 where passivating the surface of both the device
2 and handle substrates to allow hydrophobic wafer bonding comprises treating Group IV
3 elemental semiconductors, including Ge, with dilute HF etches.

1 14. The method of claim 9 where passivating the surface of both the device
2 and handle substrates to allow hydrophobic wafer bonding comprises treating Group

3 III/V and Group II/VI compound semiconductors by compound-specific chemical
4 treatments to leave a hydrophobically passivated surface for bonding.

1 15. The method of claim 1 further comprising disposing a selected material X
2 on the device substrate to enable an X-to-handle-substrate material bond with the
3 handle substrate when an exfoliated film from the device substrate is bonded with the
4 handle substrate, where material X includes epitaxially growing a strained thin film of Si,
5 or a thin layer of amorphous Si deposited at low temperature.

1 16. The method of claim 1 further comprising disposing a selected material X
2 on the handle substrate to enable an X-to-device-substrate material bond when an
3 exfoliated film from the device substrate is bonded with the handle substrate, where
4 material X includes epitaxially growing a strained thin film of Si, or a thin layer of
5 amorphous Si deposited at low temperature.

1 17. The method of claim 1 further comprising disposing a selected material X
2 on both the device and handle substrates to enable an X-to-X material bond when an
3 exfoliated film from the device substrate is bonded with the handle substrate, where
4 material X includes epitaxially growing a strained thin film of Si, or a thin layer of
5 amorphous Si deposited at low temperature.

1 18. The method of claim 3 where cleaning and/or passivating the device and
2 handle substrates to facilitate bonding comprises removing residual particle
3 contamination on the bonding surfaces of the device and handle substrates.

1 19. The method of claim 18 where removing residual particle contamination
2 on the bonding surfaces of the device and handle substrates comprises maintaining the
3 device and handle substrates at a temperature greater than 50°C during the application
4 of the CO₂ gas jets.

1 20. The method of claim 18 where removing residual particle contamination
2 comprises impinging an inert gas on the substrate at an elevated temperature to
3 remove the particles by combined physical impact and thermophoretic lifting effect.

1 21. The method of claim 1 where initiating bonding of the device substrate to
2 the handle substrate comprises controlling the temperature at which the device and
3 handle substrates are brought into contact with each other to select the strain state,
4 whereby substrate performance in high-temperature processes is improved, or a device
5 operation temperature strain is selected to adjust a device property such as bandgap or
6 carrier mobility.

1 22. The method of claim 1 where initiating bonding of the device substrate to
2 the handle substrate comprises holding the temperature of the device and the

3 temperature of handle substrates when brought into contact with each other at different
4 magnitudes to select the strain state, whereby substrate performance in high-
5 temperature processes is improved, or a device operation temperature strain selected
6 to adjust a device property such as bandgap or carrier mobility.

1 23. The method of claim 1 where after initiating bonding of the device
2 substrate to the handle substrate, the mechanical strength of the bond of the device and
3 handle substrates is improved and the ion implantation layer transfer process is
4 activated during which activation pressure is applied to the virtual substrate.

1 24. The method of claim 23 where the mechanical strength of the device and
2 handle substrates is improved by using multiple pressure-temperature increments, or
3 continuously varying pressure-temperature combinations.

1 25. The method of claim 24 where the mechanical strength of the bond of the
2 device to the handle substrate is improved by applying higher pressures to ensure
3 better substrate-substrate contact at lower temperatures prior to exfoliation where the
4 higher pressures would at higher temperatures subdue exfoliation, and then reducing
5 the pressure to a lower level prior to annealing at higher temperatures so that exfoliation
6 is uninhibited.

1 26. The method of claim 21 where controlling the temperature at which the
2 device and handle substrates are brought into contact with each other to select the
3 strain state comprises maintaining the device and handle substrates at approximately
4 equal temperatures.

5 27. The method of claim 21 where controlling the temperature at which the
6 device and handle substrates are brought into contact with each other to select the
7 strain state comprises maintaining the device and handle substrates at unequal
8 temperatures selected to control the strain state between the device and handle
9 substrates.

1 28. The method of claim 1 further comprising removing an upper portion of the
2 device film exfoliated from the device substrate, whereby a smoother and less defect
3 prone surface is provided for subsequent optoelectronic device fabrication.

1 29. The method of claim 28 where removing an upper portion of the device
2 film exfoliated from the device substrate comprises chemically polishing the upper
3 portion with a damage selective etch, or mechanically polishing the upper portion or
4 both.

1 30. The method of claim 29 where the device and handle substrates present a
2 Ge/Si interface and where chemically polishing the upper portion with a damage

3 selective etch comprises etching with a mixture of HF:H₂O₂:H₂O performed at selected
4 dilution ratios x:y:z at selected temperatures.

1 31. The method of claim 29 where the device and handle substrates present a
2 Ge/Si interface and where chemically polishing the upper portion with a damage
3 selective etch comprises etching with a mixture of HF:HNO₃:C₂H₄O₂:H₂O performed at
4 selected dilution ratios x:y:z at selected temperatures.

1 32. The method of claim 29 where the device and handle substrates present a
2 Ge/Si interface and where chemically polishing the upper portion with a damage
3 selective etch comprises etching with a mixture of H₂O₂:H₂O performed at selected
4 dilution ratios y:z at selected temperatures

1 33. The method of claim 29 where the device and handle substrates present a
2 InP/Si interface and where chemically polishing the upper portion with a damage
3 selective etch comprises etching with a mixture of HCl:H₃PO₄:H₂O₂ used in ratios of
4 1:2:2 and 1:2:4.

1 34. The method of claim 29 where the device and handle substrates present a
2 Ge/Si interface and where mechanically polishing the upper portion or both comprises
3 using a colloidal silica slurry in a KOH solution.

1 35. The method of claim 29 where the device and handle substrates present a
2 InP/Si interface and where mechanically polishing the upper portion or both comprises
3 using a colloidal silica slurry in a sodium hypochlorite solution.

1 36. The method of claim 29 further comprising performing homoepitaxy to
2 leave a smooth defect-free surface.

1 37. The method of claim 1 further comprising processing the virtual substrate
2 as a template for growth of an optoelectronic device through hetero-epitaxy.

1 38. The method of claim 1 where improving the mechanical strength of the
2 device and handle substrates comprises utilizing independently varied pressures and
3 temperatures during bonding, wherein at low temperatures, high pressures are applied
4 to strengthen the bond, and at high temperatures the pressure is then reduced to avoid
5 the suppression of layer exfoliation in the device substrate.

1 39. The method of claim 1 where improving the mechanical strength of the
2 device and handle substrates comprises applying a uni-axial load to the pair of
3 substrates during annealing at a load small enough to avoid the suppression of
4 blistering.

1 40. The method of claim 1 further comprising disposing a strain compensation
2 layer on the back surface of the handle substrate.

1 41. The method of claim 40 where the device and handle substrate interface is
2 GaAs/Si, InP/Si or Ge/Si and where disposing a strain compensation layer on the back
3 surface of the handle substrate comprises disposing a film of Ge on the back surface of
4 the Si handle substrate.

1 42. A virtual substrate comprised of:
2 an optoelectronic device substrate; and
3 a handle substrate bonded to the device substrate by means of a step
4 which improves the mechanical strength of the device and handle substrates, and after
5 which the device substrate is thinned to leave a single-crystal film on the virtual
6 substrate such as by exfoliation of a device film from the device substrate.

1 43. The virtual substrate of claim 42 where the device and/or handle substrate
2 are subjected to a pre-bonding treatment to allow the removal of a thin film prior to their
3 bonding with each other.

1 44. The virtual substrate of claim 42 where the device and/or handle substrate
2 are subjected to cleaning and/or passivating the device and handle substrates to
3 facilitate bonding together.

4 45. The virtual substrate of claim 43 where the device and/or handle substrate
5 are subjected to cleaning and/or passivating the device and handle substrates to
6 facilitate bonding.

7 46. The virtual substrate of claim 43 where the device substrate subjected to a
8 pre-bonding treatment to allow the removal of a thin film is ion implanted to inject an
9 amount of gas species into the device substrate to form the internally passivated
10 surfaces and to create an internal pressure necessary to exfoliate a layer from the
11 device substrate upon annealing.

1 47. The virtual substrate of claim 46 where the device substrate is implanted
2 with H^+ or a combination of H^+ and He^+ .

1 48. The virtual substrate of claim 44 where the device and/or handle substrate
2 subjected to cleaning and/or passivating has a passivated surface to allow hydrophobic
3 wafer bonding to each other.

1 49. The virtual substrate of claim 48 where the device and/or handle substrate
2 subjected to cleaning and/or passivating is treated to enable the formation of an intimate
3 covalent bond between a device film, exfoliated from the device substrate, and the
4 handle substrate when bonded together in the virtual substrate to allow for the ohmic,
5 low-resistance interface electrical properties.

1 50. The virtual substrate of claim 44 where the device and/or handle substrate
2 subjected to cleaning and/or passivating is treated to eliminate adsorbed water on the
3 surface of the device and/or handle substrates by means of a low temperature bake in
4 an inert atmosphere or in vacuum.

1 51. The virtual substrate of claim 50 where the device and/or handle substrate
2 is treated by means of a low temperature bake comprising baking at a temperature such
3 that the vapor pressure of water is below the partial pressure of water in the surrounding
4 ambient.

1 52. The virtual substrate of claim 42 further comprising a layer of a selected
2 material X disposed on the device substrate to enable an X-to-handle-substrate material
3 bond with the handle substrate when an exfoliated film from the device substrate is
4 bonded with the handle substrate.

1 53. The virtual substrate of claim 42 further comprising a layer of a selected
2 material X disposed on the handle substrate to enable an X-to-device-substrate material
3 bond when an exfoliated film from the device substrate is bonded with the handle
4 substrate.

1 54. The virtual substrate of claim 42 further comprising a layer of a selected
2 material X disposed on both the device and handle substrates to enable an X-to-X

3 material bond when an exfoliated film from the device substrate is bonded with the
4 handle substrate .

1 55. The virtual substrate of claim 44 where the device and/or handle substrate
2 subjected to cleaning and/or passivating is treated by removing residual particle
3 contamination on the bonding surfaces of the device and handle substrates.

1 56. The virtual substrate of claim 55 where the device and/or handle substrate
2 subjected to cleaning and/or passivating is treated by impinging an inert gas on the
3 substrate at an elevated temperature to remove the particles by combined physical
4 impact and thermophoretic lifting effect.

1 57. The virtual substrate of claim 42 where the device substrate and handle
2 substrate are bonded together by controlling the temperature at which the device and
3 handle substrates are brought into contact with each other to select a strain state,
4 whereby substrate performance in high-temperature processes is improved, or a device
5 operation temperature strain selected to adjust a device property such as bandgap or
6 carrier mobility.

1 58. The virtual substrate of claim 42 where the device substrate and handle
2 substrate are bonded together by holding the temperature of the device and the
3 temperature of handle substrates when brought into contact with each other at different

4 magnitudes to select a strain state, whereby substrate performance in high-temperature
5 processes is improved, or a device operation temperature strain selected to adjust a
6 device property such as bandgap or carrier mobility.

1 59. The virtual substrate of claim 42 where the mechanical strength of the
2 bond of the device substrate to the handle substrate is increased and an ion
3 implantation layer transfer is activated by application of pressure to the bond.

1 60. The virtual substrate of claim 42 where the mechanical strength of the
2 device and handle substrates is improved by using multiple pressure-temperature
3 increments, or continuously varying pressure-temperature combinations.

1 61. The virtual substrate of claim 60 where the mechanical strength of the
2 bond of the device to the handle substrate is improved by applying higher pressures to
3 ensure better substrate-substrate contact at lower temperatures prior to exfoliation
4 where the higher pressures would at higher temperatures subdue exfoliation, and then
5 reducing the pressure to a lower level prior to annealing at higher temperatures so that
6 exfoliation is uninhibited.

1 62. The virtual substrate of claim 42 where the surface of the device substrate
2 is treated by removing an upper portion of the device film exfoliated from the device

3 substrate, whereby a smoother and less defect prone surface is provided for
4 subsequent optoelectronic device fabrication.

1 63. The virtual substrate of claim 62 where the surface of the device substrate
2 is treated by chemically polishing the upper portion with a damage selective etch, or
3 mechanically polishing the upper portion or both.

4 64. The virtual substrate of claim 63 where the surface of the device substrate
5 is treated by performing homoepitaxy to leave a smooth defect-free surface.

1 65. The virtual substrate of claim 42 further comprising an optoelectronic
2 device fabricated in the device substrate of the virtual substrate through hetero-epitaxy.

1 66. The virtual substrate of claim 42 where the device substrate is composed
2 of one selected from the group comprising Group III/V compound semiconductors
3 (including GaAs, InP, GaN,), Group II/VI semiconductors (including CdTe,), Group IV
4 semiconductors (including Ge for GaAs family growth), and optically usable ferroelectric
5 oxides (including LiNbO₄, BaTiO₄).